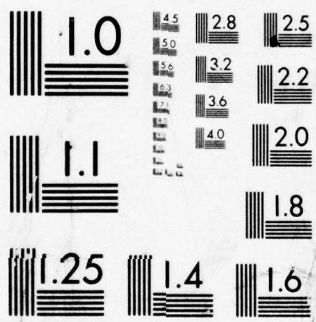
AD-A031 045 CIVIL ENGINEERING LAB (NAVY) PORT HUENEME CALIF F/G 10/1
CONCRETE FOR OCEAN THERMAL ENERGY, CONVERSION STRUCTURES.(U)
AUG 76 H H HAYNES, R D RAIL
UNCLASSIFIED CEL-TN-1448 NL

1 OF 1
AD
A031045

END
DATE
FILMED
11-76



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(12)

FG.

Technical Note N-1448

CONCRETE FOR OCEAN THERMAL ENERGY CONVERSION STRUCTURES

By

H. H. Haynes and R. D. Rail

August 1976

Sponsored by

Division of Solar Energy
U. S. Energy Research and Development Administration
Washington, D.C. 20545

CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California 93043

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: (14) CEL-TN-1448	2. GOVT ACCESSION NO.: DN687027
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): (6) CONCRETE FOR OCEAN THERMAL ENERGY CONVERSION STRUCTURES	5. TYPE OF REPORT & PERIOD COVERED: (9) Final rept. Jun 1975–Jan 1976
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): (10) H. H. Haynes and R. D. Rail	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Civil Engineering Laboratory, Naval Construction Battalion Center, Port Hueneme, California 93043	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: ~~44-017~~
11. CONTROLLING OFFICE NAME AND ADDRESS: Energy Research and Development Admin., Division of Solar Energy, Washington, DC 20550	12. REPORT DATE: (11) August 1976
	13. NUMBER OF PAGES: 47 (12) 50p.
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Concrete structures, ocean structures, pressure-resistant structures, underwater ocean thermal energy, research, state-of-the-art, cylindrical shells, hydrostatic pressure, offshore structures

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this study was to assess the state of the art of concrete technology and construction practices as they are related to the construction of massive floating structures to house ocean thermal energy conversion (OTEC) systems. The relevant capabilities and limitations of available concrete technology and construction practices are described and deficient areas are identified. Recommendations for research and

continued

391 111

lbg

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. Continued

development are given by which reasonable improvements can be made in the near term to provide greater assurances of long-term safe and reliable operation of the OTEC systems and to provide lower cost structures.

Library Card

Civil Engineering Laboratory
CONCRETE FOR OCEAN THERMAL ENERGY CONVERSION STRUCTURES (Final), by H. H. Haynes and R. D. Rail
TN-1448 47 p. illus August 1976 Unclassified

1. Concrete structures 2. Underwater ocean thermal energy I. 44-017

The purpose of this study was to assess the state of the art of concrete technology and construction practices as they are related to the construction of massive floating structures to house ocean thermal energy conversion (OTEC) systems. The relevant capabilities and limitations of available concrete technology and construction practices are described and deficient areas are identified. Recommendations for research and development are given by which reasonable improvements can be made in the near term to provide greater assurances of long-term safe and reliable operation of the OTEC systems and to provide lower cost structures.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

CONTENTS

INTRODUCTION

Objective

The purpose of this study was to assess the state of the art of concrete technology and construction practices as they are related to the construction of massive floating structures to house ocean thermal energy conversion (OTEC) systems. The relevant capabilities and limitations of available concrete technology and construction practices are described and deficient areas are identified. Recommendations for research and development are given by which reasonable improvements can be made in the near term to provide greater assurances of long-term safe and reliable operation of the OTEC systems and to provide lower cost structures.

Background

OTEC power plants are being developed to convert solar-derived energy stored as heat in the world's oceans to electrical or other man-usable forms of energy. Since the temperature differences between the warm ocean surface waters and the cold deep waters are small, the size of the thermal engines and the quantities of warm and cold water needed are very large. Therefore, the OTEC power plants are not standard construction items but represent a new type of ocean facility that has never been built before: huge floating structures on the order of several hundred feet in both vertical and horizontal directions. From the main platform hangs a cold water inlet pipe at least a thousand feet long and perhaps one hundred feet in diameter. Both moored and free floating (dynamically positioned) concepts have been proposed. The main platform may be a surface vessel, a semisubmersible, or a structure

wholly submerged several hundred feet with only an access tower to the surface.[1-5] The design and construction of such novel structures will require imagination and utilization of past experiences drawn from many engineering disciplines.

This report discusses only the topic of concrete. The main platform, the cold water intake pipe, and the anchor for OTEC structures could be built of concrete today using available technology and construction practices; however, further study at this time of selected problems with reachable near-term solutions can significantly lower costs, lessen risks, and provide longer structure life.

REQUIREMENTS FOR OTEC STRUCTURES

Scope

This study addresses the requirements of OTEC structures as a class and not the requirements of individual configurations or concepts. At present, OTEC structural concepts range from long, vertically oriented structures to moderately long, horizontally oriented structures, and from single-cylindrical-hull surface structures to multiple-cylindrical-hull submerged structures.[1-5] Requirements common to all OTEC concepts are the focus in this paper for describing current concrete technology and identifying areas for profitable research and development.

System Requirements

The basic system requirements for OTEC structural systems include:

- Capability (to perform the mission)
- Availability (to begin the mission)
- Reliability (to continue performance throughout mission life)

The fundamental requirement is, of course, to be able to construct and deploy structural systems capable of performing their service functions in the ocean environment for the design life of about 25 to 40 years (not specifically defined at this stage).

Capability. The service function of the platform is to house men and equipment in a dry one-atmosphere environment.

The cold water pipe is required to transport huge volumes of cold water with a minimum of power, head loss, and temperature change from depths of one thousand to several thousand feet.

For moored OTEC plants, an anchor or anchors is required to hold the structure on station in water depths to 20,000 feet under all environmental conditions.

Availability. The OTEC plant must be constructable and deployable. The current target schedule for OTEC development is to complete concept design by the end of 1979, a 25- to 50- Mw, prototype by 1982, and an operating 100- Mw demonstration plant by 1987. The approach to meet this schedule is (1) to utilize state-of-the-art engineering, construction, and marine operations capabilities, (2) to adapt the state-of-the-art to the OTEC application by engineering investigations, engineering development including validation testing of critical components, and extension of marine and construction methods; and (3) to generate new information from research and technology

Reliability. Throughout the 25- to 40-year life the standard of safety and degree of long-term reliability--including survival in extreme conditions--need to be high. Total loss of the facility or loss of personnel is unacceptable; however, a partial structural failure that would interrupt power generation for a limited time would be acceptable.

Structural Requirements

To provide the system requirements of capability, availability and reliability will require certain structural characteristics which are described below.

The structural requirements to provide "System Capability" are:

1. Hydrodynamic Stability. The structure must be stable as a floating/ moored vessel during construction, deployment, service, and modular assembly and disassembly (if used).

2. Positive Buoyancy. The platform supports its own self-weight, the cold water pipe, thermal and electrical equipment, and vertical component of the mooring force.

3. Controlled Variable Buoyancy. Platform buoyancy will need to be constantly compensated for changes in the density of ambient seawater, vertical forces due to waves, and - most important - the vertical component of the mooring force, which is influenced by currents, wind, and waves. Long-term increases in weight will also need to be considered because of biofouling and seawater saturation of concrete.

4. Pressure Resistant Hull. The platform will need to be pressure resistant to depths of several hundred feet in order to provide the buoyancy and the one-atmosphere housing for men and equipment.

The structural requirements to provide "System Availability" are:

1. Design and Engineering. Design requires a knowledge of the loadings, the structure's capability to resist the loadings, and analysis methods to relate the loadings to the structure's resistance.

2. Loadings. The structure will be subjected to a variable hydrostatic head; repetitive loadings and vibrations from waves, machinery, and mooring lines; and dynamic, concentrated loads at the cold water pipe connection. The cold water pipe will be subjected to tensile loads by its own weight and to significant bending and shear forces (and possibly large and small amplitude vibrations) by currents and, perhaps, internal waves. Contingent loadings such as impact due to collision and grounding must be considered.

3. Load-Resistance Capacity. To resist service and environmental loadings, the structure must provide adequate strength to bending, tensile,

compressive, torsion, and shear loads and provide overall and local structural stability.

4. Structural Analysis. Established analysis methods of working stresses, cracking strength, ultimate strength, elastic and plastic deformations, and stability--based on behavior of materials and of structural elements--will be required to analyze the OTEC structure. Other methods such as model testing, surveys of existing structures, and probabilistic design may need to be employed. Consideration will need to be given to time-dependent design for fatigue, creep, and relaxation, and to change to material properties with time.

5. Construction Methods. To construct large concrete structures methods need to be available to construct in a floating mode in shallow or deep protected waters. Also, open sea assembly of large floating components may be required. Total time of construction should be minimized. Variable positive buoyancy will be required during construction and deployment of the platform and the cold water pipe. The concrete anchor, if used, will require positive buoyancy during tow-out, slight negative buoyancy during lowering, and then heavy selfweight or engagement to the seafloor; this may require the capability to fill the anchor with grout or concrete at great depths by remote methods.

6. Availability of Resources. Size dominates the requirements for manpower, materials, and facilities. Concrete is not as labor intensive nor as demanding as steel construction for sophisticated skills; however, skilled and unskilled labor will be needed, probably around the clock. Cement, aggregates, fresh water, reinforcing and prestressing steels, and forming materials must be available at, or

readily transportable to, the construction site. A large on-land near-shore construction site, preferably with a graving basin, will be needed as will a protected shallow water site. A near-shore, protected deep water site with a deep passage to sea is highly desirable to preclude or minimize the need for expensive flotation and to minimize construction time in the open sea. The construction site will likely need to be at or near an industrial area to most economically provide trained manpower, construction equipment and supporting services.

The structural requirements to provide "System Reliability" are:

1. Design for Service and Survival Modes. The structure will probably be designed to operate in a service mode during a defined environmental condition or a defined accident condition. For sea and accident conditions beyond the service mode, the structure will be designed for survival. That is, the structure will maintain its integrity and remain afloat so that men and the facility are safe; however, power is not being generated and repairs may be needed before the plant is again in operation.

2. Safety. Safety depends on probability of failure and consequences of failure. Thus safety requires structural characteristics that will minimize probability of failure by good quality design and construction, durable materials, and so forth and that will minimize the seriousness of failure by designing for an acceptable mode of failure.

3. Noncatastriphic Failure Mode. Structural failure should be gradual and partial rather than sudden and catastrophic. This requires the use of structural redundance, the provision of structural resilience (to absorb energy without failure) and structural ductility (to accommodate deformation without failure), and the avoidance of instability failure. Accident tolerance may require sacrificial protective structures such

as fenders, compartmentalization (perhaps double hulls), and guaranteed reserve buoyancy in case of flooding. A progressive failure mode must be avoided.

4. Fire Safety. The material and structure should be highly resistant to damage by fire and capable of limiting the spread of fire.

5. Durability. The construction material (the concrete itself and the embedded reinforcing and prestressing steel) must have the long-term capability to resist degradation below a specified standard in the marine environments of atmospheric zone; splash zone; shallow water submerged zone; deep water submerged zone; and, for the anchor, near the seafloor zone and under the seafloor zone.

6. Long-Term Engineering Properties of Materials. The engineering properties of the construction material must be known over long-term exposure to the marine environment. This includes the behavior of concrete materials in the stages of partial and complete saturation with seawater.

7. Maintainability and Repairability. To provide long-term reliability and economy, the need for structural maintenance and repair must be minimized; at the same time, inspection, maintenance and repair capabilities must be available in order to detect, prevent, control and overcome material degradation that does occur. Some, but not all, OTEC concepts use a modular design to permit periodic removal and replacement of major modules to reduce downtime and permit shipyard overhaul and refit, particularly the heat exchangers; this modularity requires methods for at-sea assembly and disassembly of major structural components.[1] Some concepts visualize that remote replacement of the critical anchor-to-mooring line connection, on a scheduled or as needed basis, will be

necessary to meet the design life.[6] All OTEC power plants, including the modular ones, are too large to drydock and therefore must have the capability for at-sea inspection, maintenance, and repair.

8. Summary. Because the final structure is an integration of material behavior, structural design, construction approach, and maintenance and repair operations, the structural requirements are summarized in Table 1 as they relate to each of these major areas.

Table 1. Structural Requirements

MATERIALS

- Durability
  - Concrete
  - Embedded Steel
- High Strength
- Low Unit Weight
- Dimensional Stability
- Ductility
- Low Water Absorption; Low Permeability
- Saturated Concrete Engineering Properties
- Special Materials to Improve Engineering Properties
- Antifouling Concrete

DESIGN

- Service Loads
- Environmental Loads
- Load Resistance Capacity
- Structural Analysis Methods
- Fatigue
- Shear
- Impact
- Failure Mode

CONSTRUCTION

- Graving Dock Construction
- Construction Afloat
- Slip-forming Methods
- Conventional Intermittent Casting Methods
- Precast and Segmental Construction Methods
- Joining Techniques
- Tolerances
- Placing Concrete on Seafloor
- Quality Control
- Availability of Resources

OPERATION

- Inspection Methods
- Maintenance Methods
- Repair Methods
- Module Replacement
- Long-Term Buoyancy Changes

STATE OF ART

Floating and Submerged Concrete Structures

Concrete production is a world-wide industry using primarily local manpower and materials. Reinforcing and prestressing steels are readily available in all developed countries.

There is a great deal of long-term experience that started around the 1890's with surface and submerged concrete structures for coastal and harbor facilities, bridge piers, floating structures, and ship hulls.[7] In the past 4 years there has been a tremendous surge of development of large concrete structures for use in the open ocean, particularly the North Sea, for offshore oil drilling, production, and storage.

Concrete structures for coastal protection, dock and harbor works, and large bridge foundations in fresh and salt water are frequently constructed by combining precasting of large components (floated to the site and submerged) with in-situ concreting underwater by bucket and tremie placement, grout intrusion into prepacked aggregate, and other methods. Representative examples are the San Francisco-Oakland Bay Bridge caisson-piers, the largest of which is 197 feet long, 92 feet wide and over 500 feet high (1930's), the Richmond-San Raphael Bridge "bell piers" (1950's), the Oakland Estuary highway tunnel (early 1960's) and the 3-1/2 mile-long San Francisco Bay Area Rapid Transit (BART) Tunnel (late 1960's). Concrete multiple-pontoon floating bridges, each several thousand feet long, have been constructed, two across freshwater Lake Washington and one across saltwater Hood Canal, near Seattle (1940, 1955 and 1961), and one in Tasmania (1940). Precast pontoons, for example 360 feet long, 50 feet wide and 14 feet deep, were

towed to the site and connected by high strength bolts or by post-tensioning of epoxy-bonded joints.[8]

Many ship hulls of regular weight and lightweight reinforced concrete were built in the United States in response to steel plate shortages during World Wars I and II (about 15 ships in WWI and about 104 in WWII). A few reinforced concrete ships were built in Europe in each of the world wars. These concrete ships saw service as tankers and dry cargo carriers.[9,10] Typical WWII sizes in the U. S. were 366-foot length, 54-foot beam, 35-foot depth, and 11,000-ton displacement.[9] Concrete hulled lighters and barges were also used. An experimental U. S. Navy landing ship of prestressed concrete successfully performed many test landings on beaches in 1946 but was not put into service.[11] The concrete ships demonstrated good performance particularly in resistance to vibration, fatigue, and abrasion, but were uneconomic in the post-war periods, due, in part, to imitative designs that did not utilize the advantages of concrete, and to high self-weight-to-cargo-weight ratios.[10,11] Commercially successful prestressed concrete ocean-going barges (2,000-ton size) have been in regular service in the Philipines for the past 9 years and have performed well.[9,11] Reinforced concrete ocean-going barges have been used in the U. S. Gulf states, Mexico, South America, and Africa.[11] In 1962 a floating oil refinery was built in Belgium on a two-way, post-tensioned, compartmentalized, concrete barge about 180 feet long by 80 feet wide and was towed to Africa for service there. A major reason for choosing concrete was concrete's superior resistance to fire.[11]

A 3-year long program of detailed inspection (reported in 1972) of many USSR concrete floating dry docks found them to be, in general, in

excellent condition with very little concrete deterioration or reinforcing steel corrosion after 10 to 40 years service in various seas with different climates. The drydocks, up to 8,500 tons lifting capacity (about 425 x 105 x 48 feet in size) had been constructed by precast and in-situ methods of dense, high-strength concrete and had required a minimum of maintenance.[12]

A precast prestressed concrete floating platform has just been constructed at Tacoma, Washington. The 68,000-ton displacement vessel, 461 x 136 x 57 feet was outfitted as a liquified petroleum gas (LPG) processing and storage facility; it was recently towed to Indonesia and moored in the Java Sea. The platform was segmentally constructed in a dewatered basin and then floated. The hull, including the precast curved bottom shell elements which weighed 35 tons each, was post-tensioned longitudinally and traversely.[9]

The successful emplacement of the Ekofisk concrete oil storage tank in the North Sea in 1973 precipitated a wave of orders for concrete gravity (bottom-sitting) structures for offshore oil use.[13] Three drilling and production platforms were installed in 1975. At least 9 more, currently under construction at shallow and deep water sites in Norway, Scotland, Sweden, and the Netherlands are scheduled for deployment in 1976 and 1977 in water depths to 510 feet.[14] These very large structures are of particular interest to the OTEC program since they are floating during most of their construction and during deployment. They are usually constructed as follows. The base or bottom section is started dry in a dewatered basin near the shoreline. When the walls of the base are sufficiently high the basin is flooded and the bottom section

is moved to a protected deep water site and moored. Construction continues, usually by slip-forming the tank and tower walls on a round-the-clock basis. Sand and water ballast maintains the working level at about a 30- to 40-foot freeboard for the major part of the construction phase.[13]

The Brent B CONDEEP platform, built in Norway by the above method, is representative of the concrete offshore platforms. Brent B has an installed displacement of about 400,000 tons. Its base, composed of 19 cells, is 330 feet across; three 525-foot-tall concrete towers support the steel superstructure. The structure was towed 250 miles across the North Sea and emplaced in 460 feet of water in August 1975.[15]

Because of the present offshore construction activity, concrete societies around the world have committed much effort to defining the state-of-the-art and developing recommended standards of practice for concrete ocean structures.[16-19] This work is continuing.

Also of particular interest for OTEC applications are the outstanding advances made in the past decade in construction of large concrete structures on land such as ultrahigh-rise buildings, nuclear reactor containment vessels, and liquid natural gas (LNG) storage tanks.

Material

Well-designed, high quality concrete is an excellent marine construction material for massive, floating structures. Experience has shown a relatively long life for many marine structures with a minimum of maintenance and an ease of repair.

The following topics are various material considerations that have importance to OTEC-type concrete structures.

Durability. Durability is the long-term resistance of concrete to disintegration of the concrete itself, to corrosion of embedded steel, or both, which may interact.[20,21] In general, durable concrete for OTEC applications can be produced with a high degree of assurance by strict adherence to established methods for producing high quality, dense, sulphate-resistant concrete with low permeability.[22,23] The major considerations include proper mix design (particularly a low water/cement ratio, ≤ 0.45, and a high cement factor, ≥ 7 sacks/yd^3), use of proper materials (sulphate-resistant, e.g. ASTM Type II, cement with a C_3A content between 5 and 9%, sound, nonreactive aggregates, careful limitation of chlorides in water, aggregates, and admixtures); proper placement, compaction and curing procedures; and proper structural design and detailing (adequate cover of embedded steel, control of cracking).[22]

Durability problems that do exist are frequently the result of not following the known procedures and are often associated with extreme environments such as disintegration of highway bridge decks due to the combined effects of freezing and thawing, abrasion and high salt concentration.[23,24] For the OTEC structures, the splash zone is the most severe environmental condition. The concrete is subjected to chemical attack by sulphates, chlorides, carbon dioxide and oxygen, and physical stresses due to alternate wetting and drying, temperature differentials, shock loads from waves, and other conditions. The concrete industry is actively studying these durability problems; for example, federal and state highway engineers are developing practical field methods for polymer impregnation of existing bridge decks.[25,26] Such developments will likely be available for the OTEC structure.

Corrosion. Corrosion of reinforcement and other embedded steel is considered to be potentially the most serious durability problem although, again, corrosion can usually be controlled by using appropriate materials and procedures.[27] Steel embedded in high-quality dense concrete with a high cement factor is protected in two ways: (1) the high pH environment created by the cement passivates the steel and (2) the concrete's low permeability rate prevents resupply of seawater with dissolved carbon dioxide (which could reduce the pH) and oxygen (which is necessary for corrosion of steel). Chloride ions penetrate even dense concrete in time periods of months.[28] When in contact with embedded steel the chloride will decrease passivation protection for a given pH level. However, corrosion still does not occur if either the pH is high enough or the rate of permeability (rate of oxygen resupply) is low enough.[27,29]

Other corrosion prevention methods have been used. Cathodic protection is not considered practical in many large structures since all the reinforcing steel must be electrically bonded together. Metallic (zinc, cadmium) and nonmetallic (epoxy, chlorinated rubber) coatings of reinforcing and prestressing steel have been tried in the laboratory and in the field with mixed successes.[30] Currently, uncoated steel is preferred for both reinforced and prestressed concrete. Uncoated posttensioning tendons are grouted in watertight ducts.[22] Galvanizing, if used, should be treated with small amounts of chromate to prevent hydrogen gas formation.[31] Steel coated with nonmetallic materials must be prepared and handled very carefully (which increases cost) since even a small pinhole in the coating (due to lack of coverage or to a knick or scratch) may cause localized accelerated corrosion.

Concrete in a submerged zone is more resistant to reinforcement corrosion than concrete in the tidal, splash, or marine atmospheric zone where alternate wetting and drying permit a more rapid supply of oxygen to the reinforcing steel.[27]

The above discussion applies to the general mass of the concrete in the structure. However, portions of the structure may be attacked by corrosion for such reasons as cracked concrete due to impact or tensile loading, or other electromotive forces whose driving forces are unknown. OTEC structures will experience deep ocean pressures and extreme oxygen gradients; the effects of these factors on corrosion are not known.[32]

High Strength Concrete. Ocean structures can utilize higher strength concretes than are utilized conventionally. Field use of concrete with compressive strength of 6,000 psi is common. For floating structures, higher strengths (on the order of 8,000 to 12,000 psi) can result in thinner structural elements and thus lower weight and reduced draft. Minimum draft is usually very important during construction and tow out. Significant cost savings are realized during construction if auxiliary buoyancy structures are not required.

The state-of-the-art exists to produce high strength concretes, but problems are encountered in developing quality assurance procedures for proper field handling, placement, and curing.

Saturated Concrete. The effect of partial and full saturation on the compressive and tensile strength, modulus of elasticity, Poisson's ratio, and creep rate of concrete is unknown. A limited study explored the changes in compressive strength and quantity of seawater absorption in concrete at various simulated ocean depths.[33] It was found that

concrete strength is dependent on the degree of saturation and that 6-inch-diameter, 12-inch-long cylinders under a pressure head of 500 feet were not completely saturated after two months. Also, it was observed that compressive strength of partly saturated concrete under hydrostatic pressure showed small increases in uniaxial strength but that completely saturated concrete showed strength decreases of 10% or more compared to fog-cured concrete.

The lack of knowledge about the behavior of saturated concrete is an outstanding deficiency in the state-of-the-art. The pressure-resistant hull is a highly stressed, critical component of OTEC and the behavior of the construction material must be known.

Lightweight Concrete. Structural lightweight concrete can be readily produced with compressive strengths of 5,000 psi, and from some lightweight aggregates, strengths of 6,000 psi. Lightweight reinforced concrete saturated with seawater has a unit weight in the range of 115 to 125 pcf in air and thus less than 60 pcf submerged. This represents an in-air weight saving of 20% and a submerged weight saving of 30 to 35% or more compared to normal weight reinforced concrete which, when saturated, has a unit weight of about 155 pcf in air and 90 pcf when submerged. Lightweight, as compared to normal weight, concrete has a lower modulus of elasticity (about 60 to 75%) and, on the average, somewhat greater creep and shrinkage.[34]

Aside from the obvious advantages of lower weight, which could greatly affect the design of the cold water pipe and which might be critical in being able to produce a structure of sufficient buoyancy, lightweight concrete can be used in other ways. For equal weight structures, thicker

sections of lightweight concrete could be used than normal weight concrete and permit additional space for prestress or reinforcing steel and allow for improved impact and punching shear resistance. Highly stressed locations of the hull can be fabricated with thicker sections of lightweight concrete and thus reduce the average stress. The inelastic behavior of lightweight concrete can also aid in significant redistribution of stresses in overstressed hull locations.

An example of expanded shale lightweight concrete usage in an ocean structure is given by the USS SELMA, a 7,500-ton vessel built in 1918. The vessel is presently grounded on a beach in Galveston, Texas, and reportedly the durability of the concrete and lack of steel corrosion are outstanding features.[35]

Lightweight aggregate concretes have not been tested for their suitability in pressure-resistant structures subjected to several hundred feet of hydrostatic head. In particular, information is lacking on the permeability of lightweight concrete subjected to such pressures. Only limited information is available on seawater absorption of expanded shale lightweight concrete; experimental results were inconclusive.[36] The effect of partial and full saturation with seawater on compressive and tensile strengths of lightweight concrete is not known. In summary, there is a lack of knowledge of the engineering properties and behavior of lightweight concrete for ocean structures.

Antifouling Concrete. OTEC structures will experience marine biofouling. For example, the North Sea structures in 100-foot water depths show about 4 inches of vegetation and animal growth from the tide zone to 30-foot depth after several years of operation. Below 30 feet, 4 inches

of animal growth of mostly snail tubes is found. The maximum depth for snail tubes growth is not known at this time but existing concrete platforms in 450-foot depth will yield this data for the North Sea in the future. Growth of this magnitude will decrease buoyancy and significantly increase mooring forces. The Civil Engineering Laboratory (CEL) has pioneered in the development of an antifouling concrete.[37] Toxic chemicals are incorporated into concrete by first impregnating porous expanded shale aggregate with the chemicals and then mixing this aggregate with the other concrete ingredients. The antifouling concrete has successfully prevented marine growth for up to 4 years (limit of test) in surface waters and at a depth of 120 feet.

Coatings have been an age-old technique for short-term prevention of marine growth. New products, such as dense-polyurethane and dense-epoxies which contain no solvent to evaporate, have appeared on the market and hold promise for long-term prevention. The dense-polyurethanes and epoxies exhibit highly smooth surfaces which may prove easy to clean. However, coatings may lead to intensified galvanic cell corrosion by creating locations of differential electrical potential, because some concrete sections are wet and others are relatively dry.

Recent Developments. New materials and techniques have been researched over the last 10 years that may have application to ocean structures. Fiber-reinforced concrete is beginning to have field acceptance. Fibers of steel, glass, or synthetics are incorporated in the concrete as it is mixed.[38] The notable improvements in engineering properties are an increased tensile strength, increased ductility, and improved crack control.

Polymer-impregnated concrete (PIC) shows compression strengths of 20,000 psi, tensile strengths of 1,500 psi, and elastic moduli of 6.0×10^6 psi, and, as compared to conventional concrete, an 80 to 90% decrease in permeability and in creep.[25] A major disadvantage of PIC is its lack of ductility, but research is now being conducted to improve this property.[39] Other disadvantages are higher cost of PIC and lack of established fabrication/construction methods and experience for large structures, although such methods are currently under development.

A newly developed dry casting technique that has not yet been field-tested to any great extent yields concrete with a water-to-cement ratio of 0.30 and thus has the potential for producing precast concrete members of higher strength and lower permeability at competitive prices.[40] In this method the ingredients are mixed dry, placed in the forms without water, and compacted, after which water is introduced to fill the voids by capillary action.

The history of concrete is rich in novel approaches to improve concrete. Examples of successful innovations that are still practiced include: vacuum removal of excess water from in-place concrete, prepacked techniques in which the coarse aggregate is initially placed in forms and then intruded with grout; special compaction techniques; and use of various concrete admixtures to reduce water, control setting time, increase strength, durability, and workability, and otherwise improve the engineering properties of the fresh and hardened concrete.[41] A new super-water-reducing admixture recently introduced to the industry permits use of lower water-to-cement ratios while still providing a workable concrete mix.

Design

Environmental Loads on Structures. The design for OTEC structures to resist environment loads will be only as accurate as the input loading data. Oceanographic and meteorological data need to be compiled from probable operational sites so that valid historical data are available on currents, waves, and wind. The dominant environment load is from waves, and analytical techniques exist to predict forces due to waves. The predictions are based on wave scatter diagrams that cover significant wave heights and zero crossing periods that enable both maximum and cumulative forces to be assessed for static and dynamic conditions.

Structural Analysis Methods. Once the environmental loads are determined, the forces within the structure may be calculated. Powerful analytical methods exist, namely finite element and finite difference techniques, to predict the response of structures to external loads. The internal forces, stresses, deflections, and strains are predicted well for linear and nonlinear materials. Limitations on these methods are the accuracy of input data on material behavior and skill of the structural analyst in subdividing the structure into elements.

Design for Hydrostatic Loading. Studies on pressure-resistant concrete structures have been directed at developing design approaches to predict implosion strength. For cylinder structures, research on the effects of length to diameter, wall thickness to diameter, and different types of end closures has been conducted. Design guides have been published in the form of a handbook.[42]

Several deficiencies exist in the available design procedures when related to OTEC structures. No studies have been conducted on the effect

of large penetrations or out-of-roundness of cylinder hulls. These parameters will significantly influence the behavior of the structure. Other parameters that need to be considered are the effect of vertical and horizontal stiffeners in concrete shells and the effect of the pressure gradient between the bottom and top of cylinder structures. Horizontally oriented structures have the problem of being loaded into an out-of-round shape. For vertically oriented structures, the end-condition effects and the variable hydrostatic pressure load along the structure length complicate the definition of the critical section.

Design for Long-Term Loading. The ability to design for long-term loading of pressure-resistant structures is marginally available. Conservative estimates of the maximum stress level to which concrete structures can be safely loaded can be made from studies on concrete column members and from concrete spherical structures placed in the deep ocean. A test on 18 spherical structures with 66-inch outside diameter and 4-inch wall thickness is still in progress after 4 years of exposure to the hydrospace environment at depths ranging from 2,000 to 5,000 feet.[43] This study is producing results that have direct application to OTEC structures.

The ability to predict strength changes and creep behavior of concrete over long periods of exposure to the ocean environment is not well-established. This deficient technological area was discussed above in the Materials section.

Design for Fatigue. The fatigue behavior of reinforced and prestressed concrete in an ocean environment is not well-known. Throughout the life of

a structure, waves can impart 10^8 cycles of load, which is a significantly large number of cycles. On-land concrete is known to possess good fatigue resistance if the level of stress does not exceed 50% of the compressive strength.[44] With periods of rest between cycle loadings, the autogenous healing properties of concrete assist to improve the overall fatigue resistance. In the ocean, the randomly varying loads due to waves and lack of rest periods may require a re-evaluation of the existing design guides for fatigue.

Design for Shear. Shear is one of the more troublesome loading conditions for concrete because of the tensile component of force. It is recognized that shear stresses can be reduced by introducing precompression forces. However, design guides are not available to assist in the design of large shell structures to resist shear loads.

Punching shear is another problem for concrete shell structures. Curvature assists in resisting punching shear failures, but guides for design are lacking.

Design for Impact. The impact behavior of concrete structures has not been adequately researched. For OTEC structures, it is most desirable to understand the mechanism of impact resistance for concrete and have a means of quantifying impact behavior. Concrete has considerable capacity for strain energy absorption by reinforcing with closely spaced bars or fiber reinforcement. Guides for the design against impact loading are lacking.

Construction

Construction Methods. Three approaches are available for the construction of large concrete structures: (1) slip-forming, or similar methods in which the concrete is cast in an essentially continuous manner without construction joints; (2) conventional sequential concrete pours with water-stop cast in the construction joints (or other waterproofing methods used); and (3) joining precast elements together to build the main structure or subassemblies which are then in turn joined to each other or to the structure.

Construction Sites. As described above, construction is usually started on land and then continued afloat. The critical item for construction of OTEC structures is the availability of deep, protected waters for the construction site and natural deep waterways leading to the open ocean. For OTEC, the water depths may need to be as great as 400 feet. A preliminary search for construction sites in United States waters found no such sites. If none are available then other construction approaches will have to be developed, such as reusable auxiliary flotation structures to supply buoyancy in shallow waters or the use of modular assembly in the deep but less protected waters.

Political considerations, effects of which are not known at this time, may also strongly influence construction site availability. States such as California have legislation for the conservation of shoreline that might prohibit the construction of new flooding basins.

Other Considerations. Manpower, construction materials, and construction equipment are available and in abundant supply for building OTEC structures.

In 1971, the Navy surveyed the impact of building a mobile, ocean basing system (MOBS), a concrete structure of sufficient size to land C5A aircraft, and found that one MOBS structure (the size equivalent to about 20 OTEC structures) required only a small percentage of the annual quantity of construction materials, especially cement.[45]

Joining Techniques. Precast construction using concrete elements is an expanding industry for on-land structures. This technology is beginning to be used, quite effectively, in constructing the North Sea structures and large floating barges. The advantages are shorter construction time, less congestion at the site, and better quality control. To use precast construction requires that the elements be joined together with adequate structural integrity and watertightness under hydrostatic head. Reliable joining techniques exist; however, improvements in the technology would expand application and utilization of precast concrete. For example, in lieu of slip-forming the walls, a more rapid approach might be to use precast wall elements and slip-form the vertical joints. The critical item is the quality of the joint.

Also joining methods encompass means to couple together large structural components. This approach is frequently used for underwater construction of bridge piers and subaqueous tubes. Experience in its application to large floating structures, other than pontoon bridges in protected waters, does not exist; however, the technology does exist. Significant advancements in construction engineering techniques for joining large floating elements together could reduce construction time considerably.

Quality Control. Quality control procedures for concrete were advanced significantly by the requirements of concrete nuclear reactor containment vessels.[46] Quality control is rigorous today; however, a major flaw still exists. The basic approach in concrete quality control is to inspect constituent materials and batching, mixing, and placing equipment before use to prevent problems. Concrete is sampled at time of casting and the samples tested several days later for strength. This procedure is archaic and should be replaced by a method of testing concrete for its quality just prior to casting. It is quite important for structures resisting hydrostatic load to have concrete of uniform strength and elastic modulus. The quality of the concrete needs to be known before it is placed in the structure and not after. Technological development in testing fresh concrete is advancing. The United States Army's Construction Engineering Research Laboratory recently held a conference on rapid testing of fresh concrete; the state-of-the-art was summarized for techniques to determine the water and cement content of fresh concrete.[47] Present methods using chemical-mechanical or nuclear analyses are available for field use. They require about 15 minutes to analyze fresh concrete for water or cement content. However, limited field use was reported.

Operation

Although the North Sea structures have not yet undergone inspections, such inspections are required by law and will be conducted in the future. Therefore, by the time OTEC structures are placed in service, substantial advancements in the state-of-the-are of inspection, maintenance, and repair of concrete ocean structures will have occurred.

Inspection. A vigorous inspection program will be required in order to detect problems early so that corrective action may be taken. Three zones need inspection for different mechanisms of deterioration; these are the submerged, splash, and atmospheric zones.

The submerged zone requires underwater inspection to check for cracking of concrete due to fatigue stress, overloading conditions, or corrosion of reinforcing steel. Corrosion of reinforcing steel is unlikely in the submerged zone. Inspection for sulphate attack is warranted and will be revealed by a surface-softening effect which will permit abrasion by currents or water jets used to clean the concrete surface. [23] A rough, exposed aggregate surface may indicate sulphate attack, and hence, a more detailed inspection would be indicated.

The splash zone will be most susceptible to reinforcing steel corrosion. At advanced stages of corrosion, rust marks bleeding from the concrete surface will be observed. More serious corrosion will cause spalling of concrete cover. Less obvious corrosion problems will be harder to detect. Electrical potential difference tests can be conducted to determine the potential between different sections of concrete. When potentials are greater than 0.35 volts the probability is 95% that steel is corroding. [49] Successful field application of the half-cell potentionmeters has occurred on highway bridge-decks and buried concrete pipe.

The atmospheric zone is also susceptible to reinforcing steel corrosion but to a lesser degree than the splash zone. Particular problem locations are inside corners on overhanging or vertical sections. It is

recommended to avoid sharp corners by making rounded contours and the use of fillets.

Maintenance. Scheduled (preventive) maintenance will include such items as removal of fouling and replacement of coatings, if used. Unscheduled (corrective) maintenance will be due to unanticipated loadings or material behavior.

Repair. Two types of repair are envisioned. One type is repairing sections of concrete having corrosion of steel reinforcement and the other type is repairing damaged sections of the structure caused by impact or overload. Both types of repair are not well-developed; however, approaches to the problem are available. Remedial measures for corrosion include (1) cathodic protection, (2) repair of spalled and laminated concrete, and (3) isolation from the environment by coatings on the steel or by coating the exterior surface of the concrete.[49] The recommended approach is to remove all concrete covering the first layer of reinforcement and replace this concrete after appropriate cleaning and preparation.[50] A new approach with much promise is polymer impregnation of existing concrete. Corrosion can be terminated at whatever stage of damage it has caused by using polymer-strengthened concrete technology. Polymer impregnation of deteriorated concrete has been applied to bridge decks as an experimental method. The same techniques could be applied to concrete in marine structures. The result would be a stronger concrete than the original material and an impervious concrete that would prevent oxygen and chloride ions from reaching the steel. This same technique could be used as a preventive system; however, the cost of polymer-strengthened

concrete is several times that of regular concrete.

Damaged sections of the concrete hull can be repaired by removing cracked or crushed concrete from the damaged area. Reinforcing or prestress steel is exposed so that new reinforcement can be attached by welding or mechanical means. Prestress steel can be stressed to proper levels by jacks or screws. New concrete is cast in the damaged section. Similar repair procedures have been conducted on concrete ships and vessels built in WWI and II. Recently, the Italian government required that repair procedures be proven effective in returning a concrete dry dock to its original conditions of strength before approval was granted to build the drydock.[51] Repair methods were proven for reinforced and prestressed concrete and the drydock is presently under construction.

Buoyancy Changes. Buoyancy changes in an OTEC concrete structure can occur from animal and vegetation growth on the structure. One cause for buoyancy change that is special to concrete is water absorption with time. The designers of the structure must incorporate means for adjusting the buoyancy as water is absorbed into the concrete.

RESEARCH AND DEVELOPMENT RECOMMENDATIONS

Materials

Saturated Concrete. A study on saturated concrete is required to determine the effect of partial and full saturation on the engineering properties of concrete. It is important that the material behavior used in the analysis be that of concrete representative of the concrete condition in the OTEC structure. The field condition for the concrete in the OTEC structure will be partially saturated to fully saturated, reinforced, and prestressed concrete subjected to sustained and intermittent service loads in a hydrostatic environment. In this environment, seawater enters concrete at ambient pressure filling a portion of the void volume. Some portion of the void volume will remain at atmospheric pressure, and the concrete experiences a triaxial loading effect. The engineering properties of concrete during this partial saturation stage is dependent on the seawater absorption rate. Therefore, the rate of seawater absorption must be monitored along with the engineering properties of concrete when specimens are tested in a hydrostatic environment for compressive strength, tensile strength, modulus of elasticity, Poisson's ratio, and creep. These same engineering properties need to be obtained for fully saturated concrete. Comparison of these results to continuously fog-cured specimens is essential. This type of study will yield results for the design engineer so that an accurate analysis of the structure can be conducted using known concrete properties.

Corrosion of Reinforcement. Basic research needs to be conducted to understand the fundamental mechanism of corrosion and sources of electro-

motive force in steel-reinforced concrete ocean structures. The effects of differential oxygen concentrations and hydrostatic pressure on corrosion need to be investigated. The electromotive forces between structural elements of reinforced concrete and steel need to be analyzed. Certain portions of the OTEC structure are likely to be massive plain steel components (for example, the mooring line). The question of whether or not the reinforcing steel will be anodic to the plain steel needs to be studied. Also, information is needed on the potential effects on reinforcing steel of possible "stray electrical currents" associated with an in-water power plant, and of the presence of huge quantities of other metals such as aluminum or titanium in the heat exchangers.

Development of methods to prevent corrosion and also to passivate existing corrosion needs to be conducted. Techniques or products that produce a less permeable concrete are desirable. The effectiveness of existing methods to seal pores with crystalline compounds needs to be tested. New methods such as impregnating concrete with corrosion inhibitors should be studied. Coating techniques also should be evaluated; this includes coatings such as polymer-impregnated concrete.

A document discussing the state of art needs to be published to discuss potential corrosion problems, methods of designing against corrosion, nondestructive methods to detect incipient corrosion before the concrete is damaged, and remedial methods to inhibit further corrosion and to repair corrosion-damaged concrete. This document will provide a guide to research and development studies.

Subsequently, a handbook type of document should be published. Included in this document would be data obtained by a systematic survey of existing ocean concrete structures, particularly those that are well-documented as to specifications and actual construction. Within the United States, there are numerous such structures that would yield valuable data spanning a 50-year time period. For example, the effects of the two different environments - seawater and fresh water - on Washington State's floating concrete bridges might provide valuable data on the role of chlorides in the process of corrosion.

The North Sea concrete structures are being built to specifications that reflect present-day knowledge of durability and corrosion resistance. A program should be instituted to monitor these structures. The concrete technology used in these structures will most likely be used in the OTEC structures. One of the better assurances that the OTEC structure will perform properly will be to record how the North Sea structures perform. The North Sea structures will be inspected periodically by regulating agencies, such as Det Norske Veritas or Lloyd's of London. The inspection will be for the serviceability of the structure (i.e., is the structure still safe for personnel and environment?). It is not likely that the inspection will cover detailed research topics that would exceed the minimum level of effort to obtain certification. Perhaps a joint venture between an Environmental Research and Development Agency contractor and a regulating agency can be arranged (with the cooperation of the owner of the structure) to conduct additional studies on these North Sea structures and thus obtain data not otherwise obtained in routine inspections.

Antifouling Concrete. Development work on antifouling concrete by using toxic-impregnated aggregate needs to be conducted. High strength concretes with sufficient antifouling properties for long-term effectiveness need to be developed. The long-term effectiveness of the mixes may be improved by use of more viscous chemical solutions. Higher strengths may be obtained by using chemicals that do not interfere with the hydration or bonding processes of the portland cement. Tests need to be conducted on specimens having surface areas of several square feet and exposed to ocean sea conditions.

The bond strength of antifouling concrete when cast against normal concrete needs to be investigated. It is envisioned that antifouling concrete could be used as an overlay coating to normal concrete. It is unlikely that antifouling concrete would be used for the entire wall-thickness.

Lightweight Concrete. Research to determine the behavior of lightweight concrete for use in ocean structures - in particular, pressure-resistant structures - should be conducted. The permeability and seawater absorption characteristics need to be determined. Some tests for compressive strength, tensile strength, and modulus of elasticity of partially saturated lightweight concrete should be conducted.

Advanced development work on new lightweight aggregates would be beneficial. Aggregates that show small seawater absorption values and produce concretes of compressive strength of greater than 5,000 psi would find application in OTEC structures. Due to the additional cost of lightweight concrete compared to normal weight concrete, it is unlikely that the entire

structure would use lightweight concrete. However, the cold water pipe, upper portions of the structure, and congested reinforcing steel areas could use lightweight concrete.

Rapid Analysis of Fresh Concrete. Advanced development needs to be conducted on equipment and techniques to analyze fresh concrete. Present methods have not been field-tested and accepted to any significant degree, and their processes require 15 minutes to analyze the concrete. This time period should be reduced to 5 minutes, and the analyzing equipment and techniques should be designed for the end application of inspecting every batch of concrete placed in the OTEC structures. A program should be developed to gain field experience and to validate the techniques by comparing the field prediction with results obtained from standard control cylinders.

Design

Environmental Load Criteria. Environmental load criteria need to be developed for OTEC structures. The entire structural design is aimed at producing a structure with a given factor of safety under a given loading condition. For ocean structures, the most difficult part of the design is defining the environmental loads. Considerable effort is required on this topic area, and the importance of the item is high. For example, the early North Sea concrete structures were designed for a 100-year wave of 70 feet. After four years of additional data collection, the size of the design 100-year wave increased to 100 feet. Work is required to compile environmental data on potential OTEC sites and reduce this data to loading criteria. The use of probabilistic loading definition and design methods should be considered.

Hydrostatic Loading. Additional studies are required to improve procedures for designing against hydrostatic load. OTEC structures will be pressure-resistant hulls for the entire life of the structure. Risk analysis places hydrostatic loading as a critical item because if failure occurs the probability of catastrophic loss of the entire structure is high. The effect of large penetrations, out-of-roundness, and axial and hoop stiffeners on the implosion strength of cylindrical hulls needs to be studied. The effect of pressure gradient needs to be studied but this topic depends on whether OTEC structures will be oriented horizontally or vertically.

Computer Design Methods. Improvements to computer analysis, such as finite element or finite difference methods, should be made by incorporating valid constitutive relations for the construction material. The constitutive relations for concrete materials needs to account for applied multiaxial loading effects while the concrete is partially and fully saturated with seawater.

Design for Shear. Guides need to be developed to design for shear in large shell structures. For example, the cold water pipe at the base of the structure is under high bending and shear forces due to currents acting along the length of the pipe. The pipe will be prestressed in the axial and hoop direction. An allowable design shear strength is required for the concrete in the shell. This shear strength should be based on appropriate experimental data on saturated concrete.

Design for Impact. Guides need to be developed to design for impact loading of concrete structures. Local and large area impact loads need to

be considered. These loading conditions cover the topic of punching shear failure. Methods that quantify the strain energy absorption of concrete need to be proposed and studies conducted to verify the theories.

Design for Fatigue. Guides to design for fatigue in an ocean environment need to be developed. Tests should be conducted on reinforced and prestressed concrete members that are saturated with seawater and remain submerged during test. Initial tests should explore differences between on-land and in-seawater fatigue behavior for concrete.

Construction

Construction Methods. A comprehensive study should be conducted on construction methods. No other item can result in as significant a cost saving for the structure as improvements in the method of construction. Innovations and developments in this field usually evolve by building many of a certain kind of structure and from competition. Research and development has the potential of by-passing some of this evolution.

Significant advances in construction methods are possible. For example, the following items are highlighted:

1. Develop methods to utilize more precast elements in construction. Precast elements can be built by many subcontractors, and with proper timing, the elements only have to be assembled at the construction site. The objective is to minimize steel work and cast-in-place concrete at the job site. Innovative techniques might show that precast segments combined with slip-forming methods for the joints will increase the speed of construction over that of an entire slip-formed operation.

2. Develop improved joining methods for precast elements. New types of concretes and synthetic materials open the possibility for joining precast

elements with less time and complexity than present methods. For example, polymer concrete and sulphur concrete may permit high strength joints to be made in the field in the time period of hours.

3. Develop methods to assemble large floating structural components. The completed structure may be assembled from components that were built at different locations. The components, which are major structures themselves, will be assembled while floating. An advantage to this approach is that the components may be built in relatively shallow water which makes available more construction sites. The assembly technique should be reversible to provide for replacement of modules as discussed in the "Requirements" section.

Prestressing Systems. Development of a noncorrodible prestressing system would improve the overall reliability of the structure during long-term exposure to the ocean environment. Highly stressed steel of rather small diameter is vulnerable to corrosion and subsequent failure of the steel tendon. Synthetics, such as the new Kevlar fibers, and ceramics should be investigated for prestressing materials for concrete. Of particular interest are the failure mode and whether or not such materials undergo creep or progressive failure under long-term sustained loads. The economic and technical feasibility of using noncorroding metals and alloys, such as titanium, should also be studied.

Out-of-Roundness Measurements. Methods to measure out-of-roundness of full-scale structures need to be developed. The structural capacity of pressure-resistant concrete hulls is dependent on the out-of-roundness deviations from true circular form. Designs are based on a specified

out-of-roundness and the structure needs to be checked for conformance with specifications. Local deviations are not too difficult to determine but overall deviations from cross-sectional geometry are quite difficult to determine. For concrete structures, the failure or instability shape is dependent more on overall out-of-roundness deviations than local deviations. (For thin-walled metallic structures the reverse is true where the instability shape is controlled by local deviations.)

Operation

Inspection. Instrumentation and nondestructive test methods need to be developed to aid in inspecting and monitoring the long-term integrity of the structure and quality of the materials. Long-term strain measurements can be obtained with vibrating strain gages and Carlson stress gages; however, these measurements monitor the behavior at discrete locations. Advanced systems that monitor the integrity of structural components are desirable. Acoustic emission technology is an approach that has potential for monitoring large segments of the OTEC structure (whether fabricated of concrete or steel). When concrete is overloaded or fatigued, material breakdown progresses from microcracking to macrocracking. Every propagating crack releases strain energy and results in an emission of acoustic energy. By monitoring the sound amplitude and number of occurrences of cracks an indication is obtained as to the severity of material distress. Sensors can be placed at various locations on the structure and by use of triangulation, the location of distress can be identified for more detailed investigation.

Although a high-risk Research and Development item, acoustic emission technology should be developed to monitor the material behavior during the operational life of the structure. This nondestructive method can be employed to signal danger of a possible structural failure during adverse weather conditions or incipient failure due to otherwise undetected progressive deterioration.

Repair Methods. Repair methods will be required and need to be developed. These items, however, do not need immediate attention insofar as the North Sea Concrete structures will undergo inspection and probable repair. Techniques and methods will evolve from the North Sea experiences and will have direct application to OTEC structures.

Schedule

A schedule for the recommended research and development is given in Table 2. The schedule is coordinated with ERDA's current time-phased plan: (1) concept design completed by the end of 1979; (2) 25- to 50-Mw prototype plant completed by end of 1982; and (3) demonstration power plant in operation in the ocean by 1987.

The Research and Development topics are ranked in order of relative priority and risk. The time scale reflects an indication of duration for each topic. In some cases the length of time shown could be reduced if funding were high; in other cases the full time is required to obtain results and the work could not be accelerated effectively by an increase in funds.

Table 2. Schedule for Research and Development

Research & Development Topics	Priority	Development Risk	Year 1976	1977	1978	1979[a]	1980	1981	1982[b]
Material									
Saturated Concrete	High	Low							
Corrosion	High	Low							
Antifouling Concrete	Med	Med							
Lightweight Concrete	Med	Med							
Rapid Analysis	Low	High							
Design									
Environmental Loads	High	Low							
Hydrostatic Loading	High	Low							
Computer Methods	Med	Low							
Shear	Med	Low							
Impact	Med	Med							
Fatigue	Med	Low							
Construction									
Construction Methods	High	Low							
Prestressing Systems	Med	High							
Out-of-Roundness Measurements	Low	Med							
Operation									
Inspection	Low	High							
Repair	Low	Low							

a - Concept design completed b - Prototype structure completed

SUMMARY

Research and development topics for concrete technology related to the construction of ocean thermal energy conversion (OTEC) structures have been identified. The topic areas are in the major categories of materials, design, construction, and operation. A schedule of recommended research and development is given in Table 2 to lead to near-term advancement in deficient technological areas and to increase the data base from which OTEC structures will be designed.

REFERENCES

1. Lockheed Missiles and Space Company, Inc., Ocean Thermal Energy Conversion (OTEC), Power Plant Technical and Economic Feasibility, Vol I Technical Report, Vol II Supporting Data. Prepared for National Science Foundation Research, Applied to National Needs Program, NSF/RANN/SE/GI-C937/FR/75/1 and LMSC-DO-56566, Sunnyvale, CA, April 1975.

2. TRW Systems Group, Ocean Thermal Energy Conversion, Research on an Engineering Evaluation and Test Program, Vol 1, 2, 3, 4 & 5, Final Report. Prepared for Energy Research and Development Administration for Contract No. NSF-C958, Redondo Beach, CA, June 1975.

3. University of Massachusetts. Progress report NSF/RANN/SE/GI-34979/PR/74/1: Research Applied to Ocean Sited Power Plants, by W. E. Heronemus, et al. Cambridge, MA, 30 April 1974.

4. A. Lavi and C. Zener. Solar Sun Power Plants - Electrical Power from the Ocean Thermal Difference, paper submitted to American Society of Naval Engineers for the ASNE Day 1975 Program, 26 August 1974.

5. J. H. Anderson and J. H. Anderson, Jr. A Summary of the Anderson and Anderson Analysis of the Sea Solar Power Process, 1964 to 1972. University of Massachusetts, Technical Report NSF/RANN/SE/GI-34979/TR/73/5, March 1973.

6. Ben C. Gerwick, Jr., "Concrete Structures for 2000-meter Depth," in Ocean 75, record of combined meeting of IEEE Conference on Engineering in Ocean Environment and MTS 11th Annual meeting, San Diego, CA, 22-25 September 1975, pp. 701-704.

7. Civil Engineering Laboratory, Technical Note N-1144, History of Concrete Structures in a Marine Environment, by W. R. Lorman, Part 2 of Model Ocean Basing System - A Concrete Concept. Naval Construction Battalion Center, Port Hueneme, CA, January 1971.

8. C. C. Nichols, "Construction and Performance of Hood Canal Floating Bridge," Paper No. 9 of Special Publication SP-8, American Concrete Institute, Detroit, MI, 1964.

9. Arthur R. Anderson, "Prestressed Concrete Structures (State-of-the-Art)," Pre-print of Paper No. 11C presented at Society of Naval Architects and Marine Engineers, Vancouver, B.C., 14-17 May 1975, pp. 123-144.

10. Rowland G. Morgan, "Concrete Ships," Proceedings FIP Symposium on Concrete Sea Structures, Tbilisi, September 1972, Federation Internationale de la Precontrainte, London, 1973.

11. Ben C. Gerwick, Jr., "Design and Construction of Prestressed Concrete Vessels," Paper No. OTC 1886, Offshore Technology Conference, Houston, TX, 1973.

12. V. A. Mishutin, "Concrete Floating Dry-dock Bodies After 10 to 40 years of Use in Seas with Different Climates," Proceedings of FIP Symposium Concrete Sea Structures, Tbilisi, September 1972, Federation Internationale de la Precontrainte, London, 1973.

13. Ivar Foss, "Concrete Gravity Structures for the North Sea," Ocean Industry, Vol 9, No 8, August 1974, pp. 54-58.

14. E. M. Q. Roven, K. Hove, and O. Furnes, Det Norske Veritas Rules for Design and Construction of Fixed Offshore Concrete Structures, A Review and Outlook. Paper presented at American Concrete Institute Symposium on Offshore Concrete Structures, ACI Convention, Boston, April 1975.

15. Anonymous, "World's Biggest Oil Platform," Sea Technology, Vol 16, No. 10, October 1975, pp. 24-25.

16. Federation Internationale de la Precontrainte (FIP), Recommendations for the Design of Concrete Sea Structures, 2nd Edition, London, 1975.

17. Japan Society of Civil Engineers, Recommendations for the Design and Construction of Concrete Sea Structures, Japan (in publication).

18. American Concrete Institute Committee 357, Offshore Concrete Structures.

19. Det Norske Veritas, Rules for the Design, Construction, and Inspection of Fixed Offshore Structures, Grenseveien 92, Oslo, Norway, 1974.

20. ACI Committee 201, "Durability of Concrete in Service," ACI Journal, Proceedings, Vol 59, No 12, December 1962.

21. Bryant Mather, Durability of Concrete Construction - 50 years of Progress, Proceedings of the American Society of Civil Engineers, Journal of the Construction Division, Vol 101, No CO1, March 1975, pp. 5-14.

22. Ben C. Gerwick, Jr., "Practical Methods of Ensuring Durability of Prestressed Concrete Ocean Structures," in Durabilility of Concrete, Publication SP-47,American Concrete Institute, Detroit, MI, 1975, pp. 317-324.

23. Povinda K.Mehta and Harvey H. Haynes, Durability of Concrete in Seawater, Journal of the Structures Division, Proceedings of the American Society of Civil Engineers, Vol 101, No. ST8, August 1975, pp. 1679-1686.

24. Roger E. Carrier, et al., "Factors Affecting the Durability of Concrete Bridge Decks," in Durability of Concrete, Publication SP-47, American Concrete Institute, Detroit, MI, 1975, pp. 121-168.

25. G. W. DePuy and J. T. Dikeou, "Development of Polymer-Impregnated Concrete as a Construction Material for Engineering Projects," Polymers in Concrete, Publication SP-40, American Concrete Institute, Detroit, MI, 1973, pp. 33-56.

26. David W. Fowler, et al., "Polymer-impregnated Concrete Surface Treatments for Highway Bridge Decks," Polymers in Concrete, Publication SP-40, American Concrete Institute, Detroit, MI, 1973, pp. 9_-117.

27. Odd E. Gjorv, "Concrete in the Oceans," Marine Science Communications, 1(1), 1975, pp. 51-74.

28. R. D. Browne and P. L. J. Domone, The Long Term Performance of Concrete in the Marine Environment. Paper 5, Conference on Offshore Structures, Institution of Civil Engineers, London, October 1974, pp. 31-41.

29. George J. Verbeck, "Mechanisms of Corrosion of Steel in Concrete," Corrosion of Metals in Concrete, Publication SP-49, American Concrete Institute, Detroit, MI, 1975.

30. T. E. Backstrum, "Use of Coatings on Steel Embedded in Concrete," Corrosion of Metals in Concrete, Publication SP-49, American Concrete Institute, 1975, pp. 103-113.

31. I. Cornet, et al., "Chromate Admixture to Improve Performance of Galvanized Steel in Concrete Sea Structures," FIP Proceedings, Concrete Sea Structures, Tbilisi, 1972, Federation Internationale Precontrainte, London, 1973.

32. G. Somerville and H. P. J. Taylor, Concrete in the Oceans, Report RR SMT-7402, Cement and Concrete Association, London, August 1974.

33. Civil Engineering Laboratory, Technical Note, Seawater Absorption and Compressive Strength of Concrete at Ocean Depths, by H. H. Haynes, R. S. Highberg, and B. A. Nordby, Naval Construction Battalion Center, Port Hueneme, CA (in publication).

34. ACI Committee 213, "Guide for Structural Lightweight Concrete," Title No. 64-39, American Concrete Institute, Detroit, MI, 1967.

35. Bryant Mather, Behavior of Concrete Exposed to the Sea, Proceeding of the Conference on Civil Engineering in the Oceans II, American Society of Civil Engineers, Florida, December 1969, pp. 987-998.

36. Civil Engineering Laboratory, Special Report 52-030, Seawater Absorption by Precast Portland Cement Concrete Containing Lightweight Aggregate, by W. R. Lorman, NCBC, Port Hueneme, CA, March 1973.

37. Civil Engineering Laboratory. Technical Note N-1392: Antifouling marine concrete, by J. S. Muraoka and H. P. Vind. Port Hueneme, CA, May 1975.

38. American Concrete Institute. Special Publication No. SP-44: Fiber reinforced concrete. Detroit, MI, 1974.

39. Wai-Fah Chen and E. Dahl-Jorgensen, Polymer-Impregnated Concrete as a Structural Material, Magazine of Concrete Research, Vol 26, No 86, March 1974, pp. 16-20.

40. L. H. Willis and W. E. Willis, II, Dry-Cast 12,000 psi Concrete, Journal of American Concrete Institute, Proceedings Vol 71, No 6, June 1974, pp. N19.

41. Bureau of Reclamation, Concrete Manual, 7th edition, Denver, CO, 1966.

42. Civil Engineering Laboratory (SP-700), Handbook for the Design of Undersea Pressure Resistant Concrete Structures, by H. H. Haynes, NCBC, Port Hueneme, CA (in publication).

43. Civil Engineering Laboratory, Technical Report R-805, Long-Term Deep-Ocean Test of Concrete Spherical Structures - Part 1: Fabrication, Emplacement and Initial Inspections, by H. H. Haynes, NCBC, Port Hueneme, CA, March, 1974.

44. ACI Committee 215, Considerations for Design of Concrete Structures Subjected to Fatigue Loading, American Concrete Institute, Proceedings Vol 71, No 3, March 1974, pp. 97-121.

45. Civil Engineering Laboratory, Technical Note N-1144, Mobile Ocean Basing System - A Concrete Concept, by J. J. Hromadik, et al., NCBC, Port Hueneme, CA, January 1971.

46. ACI Committee 349, Criteria for Reinforced Concrete Nuclear Power Containment Structures, Journal of American Concrete Institute, Proceedings Vol 69, No 1, January 1972, pp. 2-28.

47. P. A. Howdyshell, Rapid Testing of Fresh Concrete, CERL-CP-M-128, Construction Engineering Research Laboratory, Champaign, IL, May 1975.

48. J. R. VanDaveer, Techniques for Evaluating Reinforced Concrete Bridge Decks, Journal of American Concrete Institute, Proceedings Vol 72, No 12, December 1975, pp. 697-704.

49. Highway Research Board Bulletin 182, Corrosion of Reinforcing Steel and Repair of Concrete in a Marine Environment, Washington, DC, 1958.

50. C. F. Stewart, Considerations for Repairing Salt-Damaged Bridge Decks, Journal of American Concrete Institute, Proceedings Vol 72, No 12, December 1975, pp. 685-690.

51. B. C. Gerwick, Jr., Prestressed Concrete Ocean Structures and Ships, Prestressed Concrete Institute, Chicago, IL, September 1975.

DISTRIBUTION LIST

SNDL Code	No. of Activities	Total Copies	
–	1	12	Defense Documentation Center
–	1	10	Division of Solar Energy
FKAIC	1	3	Naval Facilities Engineering Command
FKNI	6	6	NAVFAC Engineering Field Divisions
FKN5	9	9	Public Works Centers
FA25	1	1	Public Works Center
–	6	6	RDT&E Liaison Officers at NAVFAC Engineering Field Divisions
–	372	374	CEL Special Distribution List No. 7 for persons and activities interested in reports on Engineering Materials